Simulated Impacts of Crop Residue Removal and Tillage on Soil Organic Matter Maintenance

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Cellulosic biofuel production may generate new markets and revenue for farmers. However, residue removal may cause environmental problems such as soil erosion and soil organic matter (SOM) loss. The objective of this study was to determine the amounts of residue necessary for SOM maintenance under different tillage and residue removal scenarios for corn–soybean [*Zea mays* L.–*Glycine max* (L.) Merr.] and continuous corn rotations for a site in west-central Minnesota. We employed a process-based model (CQESTR) to evaluate management practices and quantify SOM changes over time. Results showed that conventional tillage resulted in SOM loss regardless of the amount of residue returned. Under no-till, residue amount was important in determining SOM accumulation or depletion. For the upper 30 cm of soil, average annual rates of 3.65 and 2.25 Mg crop residue ha^{-1} yr^{-1} were sufficient to maintain SOM for corn–soybean and continuous corn rotations, respectively. Soil OM in soil layers below 30 cm was predicted to decrease in all scenarios as a result of low root inputs. When considered over the upper 60 cm (maximum soil depth sampled), only continuous corn with no-till was sufficient to maintain SOM. Results from this work are important because they show that, for these management scenarios, no-till management is necessary for SOM maintenance and that determining whether SOM is accumulating or declining depends on the soil depth considered. At current yields observed in this study area, only continuous corn with no-till may generate enough residue to maintain or increase SOM.

Abbreviations: SOM, soil organic matter; SOC, soil organic carbon; CDD, cumulative degree days.

Agricultural lands may have potential to help mitigate the increasing atmospheric CO_2 concentration through photosynthetic C-fixation into crop biomass. Crop productivity has increased dramatically over the past 60 yr due to development of new cultivars and intensification of agricultural management practices, resulting in increased amounts of standing crop biomass and return of more crop residues to the soil following harvest (Burney et al., 2010; Johnson et al., 2006). This intensification of crop production increases the potential for increasing SOM, representing an effective CO_2 sink.

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Adoption of conservation management practices such as reduced or no tillage can potentially augment SOM buildup, enhancing agriculture's ability to serve as a C sink (Lal, 2003; West and Post, 2002). In contrast, Baker et al. (2007) showed that the effects of tillage practices on SOM can become negligible when total SOM is considered to soil depths >30 cm, casting uncertainty over the potential of tillage management for the goal of C sequestration at least in some systems. However, Kravchenko and Robertson (2011) showed via power analysis that the absence of significant SOM differences in some studies can be due to insufficient replication and that meaningful comparisons of SOM should be performed on each horizon separately. Therefore, it is important for studies of SOM to include soil at depths >30 cm and that appropriate analytical methods tools are employed.

On both tilled and untilled fields, the ability of agriculture to maintain SOM may be compromised by harvesting non-grain biomass (crop residues). Crop residue is anticipated to play an integral role in future domestic renewable energy production, thus reducing dependence on foreign oil and potentially offsetting anthropogenic CO_2 emissions (Perlack et al., 2005; U.S. Department of Energy, 2011). Cellulosic feedstocks such as corn stover may serve as feedstock for ethanol via fermentation or thermochemical pathways, or be gasified directly for heat and/or electricity. Concerns have been raised that harvesting of crop residues will increase the risk of soil erosion and reduce SOM, subsequently reducing soil productivity and environmental quality both on and off site (Lal, 2004, 2008; Wilhelm et al., 2007, 2010).

In considering the potential for crop non-grain biomass production, a balance should be struck among economic and energy benefits, and protection of soil productivity and environmental quality. Thus, sufficient crop residue must remain on the soil to prevent negative environmental and productivity consequences. Assessing the soil and environmental needs for crop residue depends on the agronomic and environmental constraint of greatest concern (e.g., soil fertility, SOM, erosion, etc.). While erosion control is a function of the percentage of the soil surface that is covered by crop material, SOM pools are a function of the rate of humification and mineralization, which are related to biomass C inputs (Johnson et al., 2010a). Building a sustainable bioenergy economy requires that multiple environmental and agronomic needs are met; thus, conservation considerations are needed when designing biomass harvest systems (Blanco-Canqui, 2010; Johnson et al., 2010a; Wilhelm et al., 2010).

One of the challenges to assessing the impacts of crop residue and tillage management on SOM stocks is the fact that SOM concentrations change slowly (decades) and can be difficult to detect over the course of typical field studies. Accurate assessment of changes in SOM stocks is affected by soil variability and number of samples (Schrumpf et al., 2011) as well as the duration of management practices and depth of sampling (VandenBygaart et al., 2011). Process models provide an opportunity to predict the potential impacts of a broad range of management practices on SOM storage over time and modeling approaches can provide data that are complementary to field-scale studies.

A variety of models have been developed for simulating long-term dynamics of SOM under various environmental conditions. Common models include the Century model (Parton et al., 1987) and the ROTH-C model (Jenkinson, 1990). Typically, these models are used in regional applications and have provided important insights into the size and stability of global SOM pools (e.g., Davidson and Janssens, 2006). The structure of the Century and ROTH-C models divides SOM into different compartments based on stability within the soil environment. This structure is helpful conceptually, but can be difficult to rectify with commonly-available field observations of total SOM. In contrast, the CQESTR model (Rickman et al., 2001) was developed to rely on input data that were readily available at the field scale and to evaluate the effects of varying agricultural management practices. For the present study, we opted to use the CQESTR model (Liang et al., 2008, 2009; Rickman et al., 2001) for its ability to account for management practices such as tillage that play an important role in soil disturbance and SOM stability.

The CQESTR model is a process-based model that simulates SOM dynamics through organic additions such as crop residue and manure, and losses via microbial respiration. Organic matter additions to the soil are tracked by CQESTR and decomposition is a function of N content, available water based on location within the soil, accumulated heat in degree days, and soil texture (Gollany et al., 2010; Liang et al., 2008, 2009; Rickman et al., 2001, 2002). The CQESTR model does not account for OM loss or redistribution in the landscape due to erosion; therefore, it is most suitable for application to sites where erosion is negligible. The model has been validated against several long-term data sets and has been shown to represent SOM responses to varying tillage practices and crop residue removal scenarios (Liang et al., 2008; Gollany et al., 2011) similar to the topics central to the present work.

The goals of this study are to:(i) apply a combined field- and model-based approach to evaluate the long-term (decadal) size and stability of SOM pools under different tillage and crop residue removal scenarios and to (ii) employ the CQESTR model to quantify what rates of residue removal allow for maintenance of SOM under different management practices for two experimental farm fields located in west-central Minnesota.

MATERIALS AND METHODS

Experimental Site

Two adjacent fields with replicated plots assessing SOM responses to tillage and residue harvest were located at the USDA-ARS Swan Lake Experimental Farm (45°41′ N, 95°48′ W; elevation 370 m), located in west-central Minnesota near Morris. Soils in the region are formed from calcareous loamy glacial till (Des Moines Lobe of Wisconsin glaciation). Two similar soils are found within the study area; Barnes loam (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) and Aastad clay loam (fine-loamy, mixed, superactive, frigid Pachic Argiudoll). The topography is flat to rolling and average slopes of the field plots range from 0 to 2%. The area has a 30-yr (1971–2000) mean annual precipitation of 645 mm, with 408 mm falling during the growing season from 1 April to 31 August and a mean annual temperature of 11.4°C (www.ncdc.noaa.gov/normals.html).

Field Management

Historic records of Swan Lake farm indicated that the adjacent no-till and tilled fields had been managed with contrasting N-fertilizer rates from 1997 through 2001. Half of the plots in each field received no additional N fertilizer while the other half of the plots received fall application of anhydrous ammonia at rates of 179.3 and 201.8 kg ha^{-1} for the tilled and no-till fields, respectively. Fertilizer application treatments were randomly assigned. All plots in both fields were managed in continuous corn from 1997 through 2001, and then planted with soybean in 2002 and 2003. The tilled field was plowed with a full inversion moldboard plow (~20 cm) every fall after harvest and tilled with a digger (~8–10 cm) in the spring to prepare the seedbed. Beginning in 2004, plots in both fields were converted to corn/soybean or soybean–corn rotations (in any year, half of the plots were planted in corn while the others were in soybean). In 2005, when the residue removal study was initiated, fall tillage in the tilled field was changed to a chisel plow, while the spring tillage operation remained the same. Beginning in 2005, each study field contained 32 plots (6.1 by 22.9 m) which were arranged in a complete randomized block design with four residue removal treatments, both phases of a corn–soybean rotation, and four replicates. Randomization included residue removal but not tillage practice which was established before the present study.

For the crop residue removal study, residue removal rates were the same in each field. A Carter forage harvester was used for residue removal (corn years only) at removal rates of: 0, 50, 75, and 100%. The 0% treatment harvested only grain, in addition to grain harvest the 50% treatment harvested stover from four of eight rows, 75% harvested stover from six of eight rows and the 100% treatment harvested stover from all eight rows. For the partial harvest treatments, the harvest rows were alternated so all rows would have been harvested within two cycles of corn harvest. During the soybean phase, the soybean residue was returned to the field.

Crop residue additions to the soil were determined differently for two phases of the study (Table 1). For the study period from 1997 through 2005, crop residue additions to the field were based on measured yield and a harvest index value of 0.53 for corn and 0.46 for soybean (Johnson et al., 2006). Beginning in 2005, crop residue additions were measured directly from 1 m^2 areas at two locations within each plot and average values were used to generate model inputs.

Soil Sampling

An initial set of soil samples was collected in each of the two fields in 1996 and 1997. A 2.54-cm diam., hand-push soil sampler was used to collect samples in 15 cm increments to a depth of 60 cm; such that there was four replicates from each field. Another set of soil samples was collected in 2005. For the 2005 sampling, each of the original replicates was further divided into four more replicates which were established at initiation of the crop residue removal study (each replicate was divided into two plots). This resulted in a grand total of 32 replicates sampled. It is important to note that the 32 replicates sampled in 2005 represent a more comprehensive sampling of the sites collected in 1996 and 1997 when only one set of composite samples was collected from each replicate and each tillage field (during each year). Due to the limited number of samples and inherent variability of SOC, we pooled data to determine mean values for each soil replicate (at each depth) to develop initial CQESTR model input values. Depth increments from the 2005 soil samples were different than for the samples collected in 1996 and 1997. To allow comparison against observed data from the 2005 soil samples, model results from the 30- to 45- and 45- to 60-cm-depth increments were averaged to generate a number representative of the entire 30- to 60-cm-depth increment.

Soil samples collected for bulk density analysis were dried at 105°C while samples for chemical analysis were dried at 37°C. Inorganic soil C was determined by pressure change resulting from acidification with HCl (6 M) in a closed vessel (Wagner et al., 1998). Total soil C was determined via high temperature combustion with LECO TruSpec CN analyzer (LECO Corporation, St. Joseph, MI). Soil organic C was calculated by difference. To accommodate the CQESTR model input require-

Table 1. Rates of crop residue returned annually to the soil for both phases of this study. For the study period from 1997 to 2001, corn residue was determined from yield data. From 2005 to 2008, corn residue was measured directly (as described in the text). For corn–soybean rotation, residue from the soybean years was calculated based on soybean yield.

Rotation	Treatment	Corn residue	Soybean residue	Notes:
		—— Mg ha^{-1} ——		
Continuous corn (1997–2001)	no-till, no fertilizer	2.28	na†	Residue determined based on corn yield
	no-till, N = 201.8 kg ha^{-1}	7.23	na	
	till, no fertilizer	3.93	na	
	till, N = 179.3 kg ha^{-1}	8.71	na	
Corn/soybean (2005–2008)	0% residue removal	6.09	3.78	Corn residue measured in field plots. Soybean residue determined based on yield.
	50% residue removal	3.75	3.78	
	75% residue removal	3.07	3.78	
	100% residue removal	1.23	3.78	

† na, not applicable.

ments, SOC data were converted to SOM by assuming that SOM is 58% C (Rickman et al., 2001).

CQESTR Model

The CQESTR model tracks OM additions according to their placement on either the soil surface or at depth. Once residue is added to the soil, its rate of OM decomposition is determined by: temperature, water availability, residue quality as reflected by N content, and soil texture and drainage. Residue decomposition in CQESTR is simulated based partly on cumulative degree days (CDD, summation of mean daily air temperature greater than 0°C). Residue decomposition occurs rapidly during the first 1000 CDD followed by slower decomposition through 15,000 CDD. In a typical year, west-central Minnesota has about 3500 CDD. After 15,000 CDD, plant residue is transferred to the SOM pool, which continues to undergo slow decomposition.

Inputs for the CQESTR model include crop and field management data, soils information, and local climate data. Information about local climate and crop rotations including tillage, yield and the timing and quantity of OM amendments are extracted from c-factor, crop, and operation files created by the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1997). For this study, field management notes (A. Olness and J. Rinke, unpublished data, 2000–2008) were used to determine average dates for planting, harvest, and tillage. Soil layer thickness (user defined to match sampling depth intervals), bulk density, and initial OM content are input directly into the CQESTR software by the user. More detailed information about the CQESTR model can be found in Rickman et al. (2001) and Liang et al. (2009).

Model inputs were organized based on data available from two field studies conducted on these plots. One set of model input files were developed from management notes from 1996 to 2004 while a second set of model inputs were developed to reflect management from 2005 to 2009 of an ongoing experiment.

Statistical Analysis

Rates of SOM change were determined using the slope function for a fixed period of model output from each portion of the study. To compare rates of SOM change under different management scenarios, the model was run for a simulation period of 25 yr and the rate was computed on model output data for the 10-yr interval from Years 15 to 25. This allowed total decomposition of initially added crop residue and transfer of C from labile pool to passive C pool; permitting us to avoid any model artifacts that occurred during the first few years of model simulation as crop residue and SOM pools were being established (a similar approach was employed by Alvaro-Fuentes et al. (2009) when using the Century model). A separate set of simulations that directly followed field conditions were conducted to generate simulation results for comparison against observed SOC data from samples collected in 2005.

Statistical tests were performed with the JMP software package (SAS Institute Inc., Cary, NC). Observed SOC concentrations from 1996/1997 were compared against those from 2005 via a matched pairs *t* test after grouping samples by tillage and crop residue inputs (influenced by fertilizer application rate during that portion of the study). To determine tillage and either fertilizer application rate or residue removal rate effects on crop yield, an ANCOVA was applied with tillage as a fixed factor and either fertilizer application rate or crop residue removal rate as a covariate. It is important to note that, in the field study, fertilizer and residue removal treatments were replicated within each tillage field, but tillage treatments were not replicated nor randomized. Crop yield and residue data measured in the field were primarily used to help develop representative inputs for the CQESTR model. Effects of tillage and crop residue on SOM discussed here are based on model outputs from several years of simulation. Analysis of covariance was also applied to evaluate output from the CQESTR model; simulated SOM accumulation or depletion was the response variable while tillage was a fixed factor and crop residue was a covariate. Determinations of statistical significance were made at the $\alpha = 0.05$ level.

RESULTS

Crop Yields

Corn yields from 1997 through 2001 (continuous corn) were affected by both tillage treatment ($p < 0.0001$) and fertilizer application rate ($p < 0.0001$; data not shown). For treatments receiving no fertilizer, mean corn grain yields were 2.57 (± 0.09) and 4.71 (± 0.12) Mg ha^{-1} for no-till and conventional-till plots, respectively (standard error values are shown in parentheses). For treatments receiving fertilizer, mean corn grain yields were 8.20 (± 0.13) and 10.05 (± 0.08) Mg ha^{-1} for no-till and conventional-till plots, respectively. These corn yields were used as inputs to RUSLE2 to determine crop residue rates for the 1997 to 2001 portion of the study.

From 2005 to 2008, corn yields were greater in chisel-till plots compared to no-till plots (ANOVA; $p < 0.0001$) while soybean yields did not vary with tillage (data not shown). Corn yields from chisel-till and no-till plots were 10.41 (± 0.18) and 8.64 (± 0.25) Mg ha^{-1}. Soybean yields were relatively consistent throughout the study period and did not vary with tillage or residue removal rate treatments. Therefore an overall mean soybean grain yield of 3.01 (± 0.06) Mg ha^{-1} was used to develop model inputs for soybean years.

Crop Residue

Crop residue return rates are summarized in Table 1. There was variability in the mass of corn residue remaining among different residue treatments (Fig. 1); however, there was no difference in corn residue between tillage treatments and mean values were used to generate CQESTR model input files.

Observed Soil Organic Carbon

Baseline SOC concentrations from 1996/1997 ranged from 29.9 g kg^{-1} in surface soils to undetectable at 60-cm depth. Within a given replicate and soil layer, the standard deviation of

SOC measurements ranged from 1.2 to 6.6 g kg^{-1}. As expected, the coefficient of variation (CV) was least in surface soil layers (13.1%) where SOC concentrations were highest and increased with depth as SOC concentrations decreased; mean CV values were 12.9, 27.4, and 80.8% for 15- to 30-, 30- to 45-, and 45- to 60-cm-depth increments, respectively. When grouped by tillage and fertilizer application rate (the first management phase of the study before the residue removal experiment), measured SOC concentrations in 2005 were not significantly different from 1996/1997 (matched pairs *t* test).

CQESTR Model Results

CQESTR-predicted SOC concentrations were compared against observed values measured in 2005 to assess model performance following 9 yr of simulation. There was strong agreement between observed and model-predicted SOC data (Fig. 2) with the model able to predict 84% of the variability observed in the measured SOC values.

CQESTR output showed different effects of residue removal depending whether or not the field was tilled (Fig. 3). In all cases, conventional tillage resulted in depletion of SOM in the upper 30 cm of soil (Fig. 3a). For no-till treatments in the upper 30 cm of soil, the mass of SOM increased proportionally to the amount of crop residue returned. Under a corn–soybean rotation, a minimum crop residue amount of roughly 3.65 Mg ha^{-1} yr^{-1} (2-yr average includes both corn and soybean residue with all soybean residue returned to the soil) is necessary to maintain current SOM levels in the upper 30 cm of soil. Under continuous corn, minimum crop residue of 2.25 Mg ha^{-1} yr^{-1} is predicted as sufficient to maintain current SOM levels (Fig. 3a).

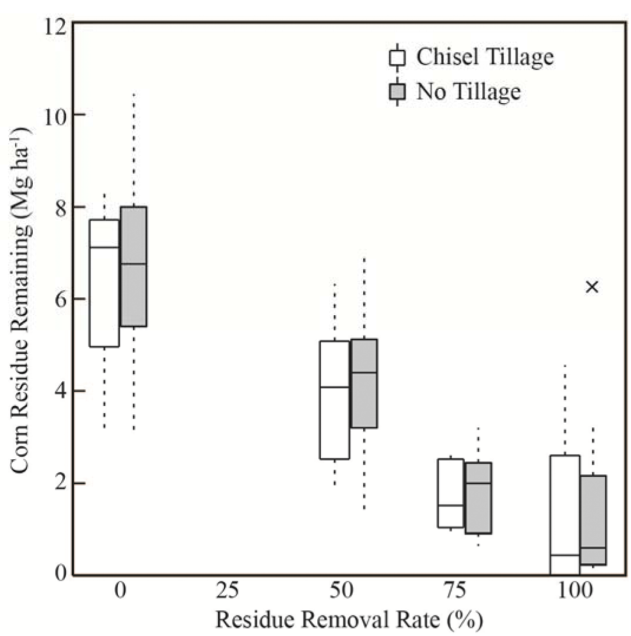

Fig. 1. Corn residue remaining on the field following residue removal treatment. For each residue removal rate, the mean value was used to generate CQESTR model input. The box denotes the median and interquartile range. Whiskers extend to values that lie beyond the interquartile range and the "x" denotes an outlier beyond 1.5 times the interquartile range.

When SOM is evaluated over the upper 60 cm of soil (the maximum depth sampled), conventional tillage did not respond strongly to the rate of stover harvest. In contrast, a positive relationship between the rate of residue return and SOM accumulation was observed (Fig. 3b) for no-till treatments. Despite this positive relationship, the crop residue returned in the corn–soybean rotation was insufficient to shift from SOM loss to accrual but it did approach levels that could sustain the current SOM pool. Assuming continued linearity between residue return and the rate of SOM accumulation, about 6 Mg ha^{-1} yr^{-1} is predicted for the humification rate to exceed the mineralization rate. This is nearly twice the 3.6 Mg ha^{-1} yr^{-1} of crop residue inputs in the continuous corn no-till treatment required to move from SOM depletion to accrual.

DISCUSSION

While it may be tempting to interpret the close agreement between observed and model-predicted and SOC values (Fig. 2) as a strong indication of model performance, it is important to note that SOC concentration changes over this portion of the simulation (1996–2005) were minimal and reflect the influence of initial SOC values measured in 1996/1997 which were used to generate model inputs. It is more appropriate to rely on data from other long-term studies such as Liang et al. (2008, 2009), which include some cropping experiments exceeding 100 yr, to conclude that the CQESTR model is able to simulate SOC dynamics over time. The lack of statistically significant change in measured SOC may be due to the lack of suitable sampling density, especially in the soil samples collected in 1996/1997. Schrumpf et al. (2011) showed that, with a sampling density of 100 points per site, the minimum detectable change in SOC from agricultural soils to be about 105 g C m^{-2} (1.81 Mg SOM ha^{-1}

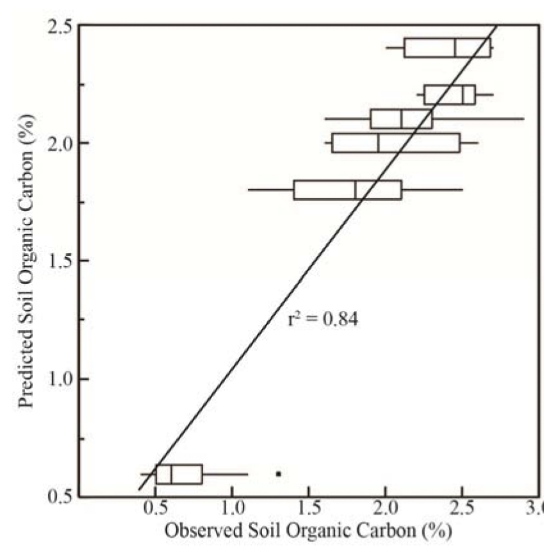

Fig. 2. Comparison between CQESTR-predicted SOC concentrations and measured values in 2005. The box denotes the median and interquartile range of observed data points. Whiskers extend to values that lie beyond the interquartile range and the point denotes an outlier beyond 1.5 times the interquartile range. The line and r^2 value reflect a simple linear regression between observed and predicted soil organic carbon (SOC) values.

when converted to units used in Fig. 3a and 3b). Under the scenario of greatest modeled change (no-till continuous corn with high residue inputs, Fig. 3a) with a sampling density of 100 points per site, it would take roughly 2.5 yr for SOC to change enough to be measurable and statistically significant. For the data presented here, sampling density is much lower; two sampling points per replicate during 1996/1997 and eight sampling points per replicate in 2005. This highlights the challenges associated with tracking SOC responses to agricultural management practices over relatively short time spans as well as the insight that can be gained by coupling data derived from simulation modeling

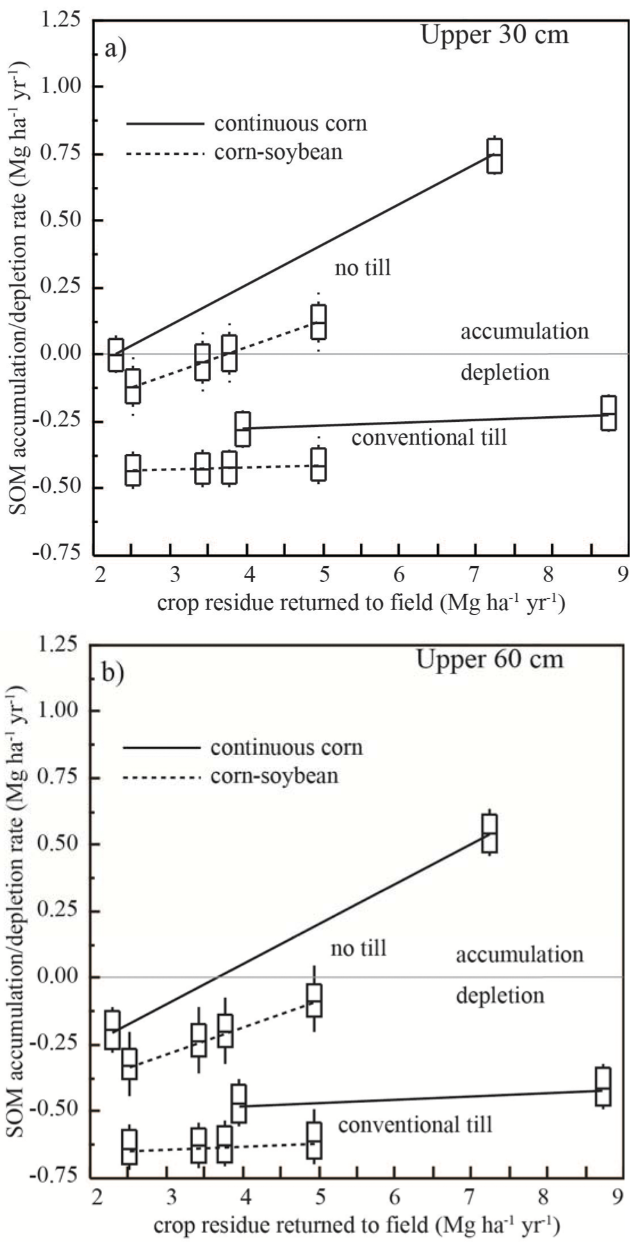

Fig. 3. Predicted effects of crop rotation, tillage, and crop residue levels on soil organic matter (SOM) accumulation or depletion in the upper 30 and 60 cm of soil (panels a and b, respectively). Crop residue values are annual average and include soybean residue for data representing plots with corn–soybean rotation. The box denotes the median and interquartile range. Whiskers extend to values that lie beyond (but are <1.5 times the value of) the interquartile range.

with data obtained via direct observation. Field experiments and additional soil sampling associated with this study are ongoing.

Under no-till management scenarios, SOM in the upper 30 cm of soil is directly influenced by both the quantity and quality of crop residue. Under continuous corn scenarios, a crop residue rate of approximately 2.25 Mg ha^{-1} yr^{-1} was sufficient to maintain current SOM levels at our study site. Under a corn–soybean rotation, however, crop residue levels of roughly 3.65 Mg ha^{-1} yr^{-1} are necessary to maintain SOM. Absent any large difference between C/N ratios of corn and soybean residue (discussed below) we attribute this to differences in friability of crop residue. Soybean residue is more fragile than corn residue and is more affected by soil disturbance in the CQESTR model (even in no-till plots, disturbance still occurs via anhydrous ammonia injection and planting). Residue C/N ratio has been shown to influence the rate of decomposition (Nicolardot et al., 2001) and CQESTR includes N content as a factor influencing decomposition (Rickman et al., 2002). It is not likely to play a large role in the results presented here, however, because the N content of soybean residue used in this study is similar to that of corn residue (0.85% for soybean straw, from Meisinger and Randall [1991] vs. 0.71% for corn residue measured). These results are similar to CQESTR model results reported by Gollany et al. (2010) for a site in South Carolina in showing that predicted SOC levels are proportional to residue inputs and greater for conservation tillage compared against conventional tillage (disking). In contrast, results in Gollany et al. (2010) showed increases in SOC under conventional tillage while we observe SOC losses, regardless of residue inputs. More direct comparison of results from these studies is complicated by differences in climate, crop rotation (and growing season length), and soil layer thickness.

Converting crop residue amount to mass of C gives minimum levels for SOM maintenance of approximately 0.95 and 1.55 Mg C ha^{-1} yr^{-1} for continuous corn and corn–soybean, respectively, under no-till management in the upper 30 cm of soil. These values are within the low end of the range (2.5 ± 1.7 Mg C ha^{-1} yr^{-1}, n = 28) of empirical values reported in literature reviewed by Johnson et al. (2010b), which included a range of crop and tillage practices. In contrast to empirical reports of a strong relationship between OM inputs and SOC in tilled fields (Allmaras et al., 2004; Larson et al., 1972; Pikul et al., 2008) the modeled prediction for the tilled field suggest that a steady decline in SOM occurs regardless of input levels when tilled. The decline in SOM predicted by CQESTR model output for the tilled field does, however, agree with a study by Clapp et al. (2000), which showed that SOC in the upper 30 cm generally decreased under moldboard plots while corn stover additions increased SOC in fertilized no-till plots. Likewise, other empirical work on similar soil in western Minnesota by Reicosky et al. (2002) showed that moldboard tillage caused a loss of SOC in the upper 20 cm of soil during a 30-yr study even when all corn residue was returned. The agreement between model results reported here and empirical results is best for those studies from west-central Minnesota (Clapp et al., 2000; Reicosky et al., 2002) and disagreement between model results and observed data occurs for sites in east-central Minnesota (Allmaras et al., 2004), Iowa (Larson et al., 1972), and South Dakota (Pikul et al., 2008). This suggests that regional differences in climate, crop, and soil conditions are important considerations when determining crop residue levels necessary to maintain SOC for varying management practices. Overall, these results suggest that the CQESTR model is adequately modeling the influence of aboveground inputs and tillage on long-term stability of SOM for nearly-level sites in west-central Minnesota. This is important because, when validated against observed data, it suggests that the model can be meaningfully applied to a range of alternative scenarios including differences in cropping systems and climate change.

It is notable that, regardless of crop yield and tillage practices, these results predict that SOM in deeper soil horizons is in long-term and steady decline, similar to results reported by Liang et al. (2009). When changes in SOM were integrated over the top 60 cm of soil, all of the corn–soybean simulation results showed overall loss of SOM, although the 0% residue removal treatment under the no-till scenario did come close to levels necessary to maintain SOM (Fig. 3b). Gregorich et al. (2001) showed that, over the course of a 35-yr study in southeastern Ontario, SOC from 20- to 70-cm depth under continuous corn decreased by about 0.57 Mg C ha^{-1} yr^{-1} when compared against grassland and forested plots. CQESTR predictions of SOC decline under continuous corn with moldboard tillage were similar to, but more conservative than, empirical values reported by Gregorich et al. (2001); with an average CQESTR-predicted decrease of 0.19 Mg C ha^{-1} yr^{-1} for soils from 15- to 60-cm deep. In contrast, continuous corn scenarios under no-tillage still maintained a possibility for buildup of SOM in the upper 60 cm of soil provided that at least 3.6 Mg ha^{-1} yr^{-1} of corn residue was returned to the field (1.52 Mg C ha^{-1} yr^{-1}). Again, this is within the range of empirical values in literature reviewed by Johnson et al. (2010b) and also in agreement with recent results shown by Follett et al. (2012) and Halvorson and Schlegel (2012).

Results reported here help to shed light on the mechanisms that may be responsible for the seeming incongruence between studies that showed benefits of conservation tillage practices on SOM in surface soils (Lal et al., 2003; West and Post, 2002) and the work of Baker et al. (2007) which showed that tillage had no effect when SOM was considered to greater depths (conservation tillage is still beneficial in providing erosion control, however). Our data show that conservation tillage practices are beneficial to SOM in surface soils while the entire soil profile can still be losing C overall. Additionally, Schmidt et al. (2011) suggest that SOM (especially in deeper soil layers) originates from root-derived exudates and microbial products rather than incorporation of aboveground biomass into deeper soils. This argument is further supported by empirical data showing that SOC in deep soil layers under switchgrass (*Panicum virgatum* L.) was greater than that observed under cultivated crops (Liebig et al., 2005) as well as a study by Gregorich et al. (2001) which showed that rotations which included alfalfa (*Medicago sativa* L.) maintained deep SOC better than continuous corn over the course of a 35-yr study. Taken together, these results suggest that important additional steps beyond conservation tillage may be necessary to replenish SOC in deeper soil layers. In agricultural ecosystems, this may mean exploring alternative cropping systems that include crops with deeper rooting systems such as alfalfa or switchgrass. Avenues for long-term buildup of SOM should include selecting for plants with large and deep root systems.

CONCLUSIONS

Results from this study show that crop rotation, tillage practices, and the rates of crop residue addition to soil can be important in determining the long-term sustainability of SOM in the upper 30 cm of agricultural soils. While the benefits of crop residue and SOM are many, whole-profile (0–60 cm) accounting of SOM shows that long-term declines of the SOM pool likely are occurring as a result of losses in deeper soil layers, especially in soils under corn–soybean rotation, which is common in the Midwest. In this context, no-till practices are helpful in that they reduce the rate of whole-profile SOM decline by accumulating SOM in the surface. Fields managed in continuous corn and no-till are one of the cropping systems that could maintain or increase accrued SOM in relatively flat fields in the Midwest.

When considered in the context of relying on agricultural lands to provide feedstock for domestic biofuel production, results from this study are important for identifying which suites of management practices may be most suitable for crop residue harvest without sacrificing SOM. Under a corn–soybean rotation at current yields in our study area, no crop residue should be removed if the soil is being managed with a goal of SOM maintenance. Under continuous corn with no-till management, SOM may be maintained or increased if crop residue returned to the field is approximately 3.6 Mg ha^{-1} yr^{-1} or greater. These results suggest that, for climate, crop rotations, and soils typical of west-central Minnesota, sustainable crop residue harvest may only be achieved under no-till management of fields planted in continuous corn. Additional strategies for maintenance or build-up of SOM should include alternative perennial crops or grasses with more extensive root systems that can contribute to SOM deeper in the soil profile.

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